Impurity Control by Intrinsic and Pellet Induced Instabilities in Fusion Devices

Synopsis of the Doctoral Dissertation

Eva Belonohy

Supervisor: Sándor Zoletnik, PhD

MTA KFKI RMKI Department Plasma Physics

Doctoral school:	**ELTE TTK Physics**
Head:	**Dr. Ferenc Csikor**
Program:	**Materials and Solid States Physics**
Head:	**Dr. János Lendvai**

ELTE TTK - 2011

Introduction

The accumulation of impurities in fusion devices is one of the most severe problems in modern fusion plasma physics en route to ITER, the first experimental fusion reactor experiment. The presence of high Z impurity ions coming mainly from the surrounding solid surfaces can give rise to significant radiation losses of the plasma energy that may cause the plasma discharge to end abruptly. Diluting the fuel, the concentration of Helium from the fusion reaction is another problem to be solved. The methods under investigation to control the impurity influx and provide an outward transport commonly involve instabilities of the plasma edge, such as the Edge Localized Modes (ELMs). Although ELMs provide sufficient periodical outward transport of particles, they also pose a grave danger to the device if uncontrolled by their large heat loads onto the first wall elements.

Presently one of the methods under development for ELM control is the injection of small cryogenic hydrogen isotope cubes, called pellets into the plasma. The pellets trigger ELMs thereby increasing the frequency of ELMs and reducing their magnitude. Injection of pellets from the inner side, that is the magnetic High Field Side (HFS) of the device is also the established main fuelling method foreseen for the ITER experiment. In case of HFS injections the ablating material is accelerated toward the center of the plasma due to the gradient of the magnetic field, thereby increasing the fuelling efficiency significantly. The penetration depth of the pellet is a key parameter in both cases, in ELM control and fuelling.

Another way to handle the impurity problem is the development of stable ELM-free discharges, where another edge plasma instability provides the required impurity control posing less thread to the first wall components of the fusion experiment. The High Density H-mode (HDH) is one of such special, stable ELM-free operational scenario found in the German Wendelstein 7-AS fusion device, where impurities are immediately flushed out of the plasma upon entering. The mechanism responsible for the low impurity concentration of the operational regime has not yet been identified.

Aims of the doctoral dissertation

The doctoral thesis is focused on the two mentioned facets of impurity control with the following aims:

- Set up an international database of HFS pellet injection events from multiple fusion devices containing besides pellet parameters, plasma parameters that might be relevant in the ablation process.
- Investigate the dependence of HFS pellet penetration depth on various pellet and plasma parameters with statistical methods and establish an HFS pellet penetration depth scaling.
- Compare results obtained from the statistical analysis to other known experimental penetration depth scalings and theoretical ablation models.
- Explore plasma instabilities present in the high density H-mode regarding their possible involvement in impurity transport.
- Characterize a plasma instability unique to HDH phase (if found) and analyze in detail its relation to the impurity transport.

Applied methods

In order to understand the physics of ELM control and fuelling by injection of pellets into the plasma I have analyzed existing experimental data as well as my own dedicated pellet discharges with statistical methods. I have first established a pellet database using measurements of 14 plasma and pellet diagnostics with my analysis tools written in the IDL programming language. To describe the database I have used statistical moments and correlation matrix. I have analyzed the pellet penetration depth dependences using the SAS statistical package.

In the second part of the thesis I have attempted to find the mechanism controlling the impurity transport in the high density H-mode of the Wendelstein 7-AS stellarator. An empirical model established on experimental results predicted the additional transport mechanism to reside in the plasma edge previous to my work, however this mechanism has not been found. To find this mechanism I have analyzed electron density fluctuations measured by the Lithium Beam Emission Spectroscopy (Li-BES) and magnetic fluctuations measured by Mirnov coil arrays using correlation and Fourier techniques to investigate plasma instabilities regarding their possible role in impurity transport. I have found an instability unique to the HDH regime characterized the mode itself and its relation to impurity transport. Unfortunately there was no possibility to perform new measurements, as the W7-AS device had been shut down in 2002.

Theses

1) I have set up a pellet database on pellets injected from the high field side of the German ASDEX Upgrade and French Tore Supra tokamaks containing pellet and relevant plasma parameters. This is the first international database containing sufficient number of pellet events required for statistical analysis. [P1]

The database presently consists of 736 ASDEX Upgrade and 81 Tore Supra pellet events later extended by 9 pellet events from the American DIII-D tokamak. I have used measurements from 14 plasma diagnostics to obtain 25 pellet (penetration depth, mass, velocity) and plasma parameters (e.g. magnetic field, plasma current, electron density and temperature) including a description of the heating scenario and plasma geometry as well.

2) I have analyzed the dependence of the penetration depth of HFS pellets on pellet and plasma parameters based on the ASDEX Upgrade dataset and established the first penetration depth scaling for pellets injected from the high field side of an experiment. [P1]

Using two statistical methods I have analysed the statistical importance of various pellet and plasma parameters in the pellet penetration depth. I have determined that there are five parameters (pellet mass, velocity, electron temperature, magnetic field and a geometrical factor) statistically important and established penetration depth scaling based on pellets injected from the high field side of the ASDEX Upgrade experiment. I have further analysed the linearity of each parameter and the effect of measurement errors on the scaling.

3) I have compared the results of the statistical analysis to the experimental penetration depth scaling of pellets injected from the magnetic low field side of fusion experiments. I have also transferred a theoretical ablation rate scaling and simulation results of two pellet ablation models into penetration depth scalings and compared these to my results. [P1,P2]

To compare the obtained experimental to theoretical models, I have first established theoretical penetration depth scalings for two pellet ablation models, the neutral gas shielding model and the Hybrid ablation code, based on a database containing pellet ablation simulation data. In case of the neutral gas shielding model I have investigated the effect of different electron temperature and density profiles on the penetration depth scaling, and have used a typical experimental electron temperature and density profile measured at

ASDEX Upgrade to set up the final theoretical scalings. I have found good agreement in case of the pellet mass and electron temperature comparing the obtained theoretical and experimental scalings and the available penetration depth for LFS pellet injections. The main differences were the log-quadratic dependence on pellet velocity, the negligible role of electron density and the presence of a magnetic field dependence.

4) I have planned dedicated plasma discharges to provide single parameter scan for the magnetic field dependence, where a significant deviation had been found between the statistical analysis and the theoretical models. The results of these experiments support my statistical results. [P7]

I have planned for dedicated plasma discharges to investigate the magnetic field and electron temperature dependence of the penetration depth in detail. In the experiments I have kept the main pellet and plasma parameters constant and applied heating scan to achieve different plasma temperature at 3 different magnetic field values. The results of these experiments confirmed the negative magnetic field dependence found in the statistical analysis that can play a significant role at the higher magnetic field of ITER.

5) I have analyzed electron density and magnetic fluctuations at the W7-AS stellarator based on measurements carried out with Lithium beam emission spectroscopy and Mirnov coil arrays in order to find a mechanism responsible for the low impurity concentration of the high density H-mode regime. [P6]

I have analysed electron density fluctuations measured by the Lithium beam emission spectroscopy with Fourier and correlation techniques, however I could not find a plasma instability unique to the high density H-mode regime. *In the magnetic fluctuations measured by Mirnov coil arrays I have found three plasma instabilities, a low and high frequency mode and a quasi-coherent mode. The latter appeared promptly at the transition to the HDH phase of the discharge, thus further studies focused on this mode.*

6) In the HDH regime I have identified a quasi-coherent mode, whose amplitude correlates surprisingly well with changes in the impurity radiation making it a promising candidate for the mechanism providing the enhanced impurity transport in this regime. I have analysed its relation in detail to impurity transport. [P3,P4,P5]

I have compared the spectral amplitude of the quasi-coherent mode from Fourier analysis to the changes observed in the impurity radiation. The appearance and disappearance of the quasi-coherent mode coincide with the decrease and increase of impurity radiation and the transition and backtransition of the HDH mode. Furthermore on smaller time scales burst in the quasi-coherent mode amplitude correlate well with the sudden stop or decrease of the impurity radiation.

7) I have obtained the spatial and temporal characteristics of the quasi-coherent mode and gave a limit on its radial position. I have analysed other available fluctuation measurements on W7-AS, however found that due their frequency range, localisation and/or simply the high density values, they cannot provide more information on the mode. I have compared my results to other fusion experiments. [P3, P4,P5]

The quasi-coherent mode is a high frequency (90-120kHz) with high poloidal mode number (m~40) localized to the inner side of the device at the toroidal location of the Mirnov coil array. Its radial location is hard to determine. As the Lithium beam emission spectroscopy measuring in the plasma edge cannot detect it and at the same time the Mirnov coils can only detect it large cross-section plasmas, it is probable that it resides in the plasma edge but not in the outer 1-2 cms. The properties of the quasi-coherent mode are similar to the results obtained at the Alcator C-Mod tokamak in a similar regime called Enhanced D_α *regime. Due to the complex 3D geometry of W7-AS and the high density of the HDH regime, presently there is no possibility to obtain information on the nature of the QC mode by theoretical turbulence simulation.*

The dissertation is based on the following publications:

P1. E. Belonohy, O.J.W.F. Kardaun, T. Fehér, K. Gál, S. Kálvin, G. Kocsis, K. Lackner, P.T. Lang, J. Neuhauser and the ASDEX Upgrade Team
„A high field side pellet penetration depth scaling derived for ASDEX Upgrade"
Nuclear Fusion 48 (2008) 065009
[refereed journal, impact factor: 3.303, citations: 3 out of 4 independent]

P2. K. Gál, E. Belonohy, G. Kocsis, P.T. Lang, G. Veres and the ASDEX Upgrade Team
„Role of shielding in modeling cryogenic deuterium pellet ablation"
Nuclear Fusion, 48 (2008) 085005
[refereed journal, impact factor: 3.303, citations: 2 independent]

P3. S. Zoletnik, M. Agostini, E. Belonohy, G. Bonhomme, D. Dunai, P. Lang, P. Garcia-Martinez, A.D. Gurchenko, C. Hidalgo, A. Kendl, G. Kocsis, C. Maszl, K. McCormick, H. W. Müller, S. Spagnolo, E. Solano, S. Soldatov, M. Spoalore, Y. Xu
„Summary of the Workshop on Electric Fields, Structures ans Self-organisation in Magnetized Plasmas (EFTSOMP) 2009. 6-7 July, 2009, Sofia, Bulgaria"
Nuclear Fusion,50 (2010) 047001
[refereed journal, impact factor: 3.303, citations: 0]

P4. E. Belonohy, G. Pokol, K. McCormick, G. Papp, S. Zoletnik and the W7-AS Team
„A Systematic Study of the Quasi-Coherent Mode in the High Density H-mode Regime Of Wendelstein 7-AS"
PLASMA2007 – International Conference on Research and Applications of Plasmas Greifswald, Germany, 2007
AIP Conference Proceedings **993** (2007) 39-42
[refereed journal, no impact factor]

P5. E. Belonohy, A. Bencze, G. Papp, G. Pokol, K. McCormick, S. Zoletnik and the W7-AS Team
„Density and Magnetic Fluctuation Studies on the Wendelstein 7-AS Stellarator"
34^{th} EPS Conference on Plasma Physics, Warsaw, Poland
Europhysics Conference Abstracts **31F** (2007) P-2.046
[conference proceedings, known citations: 3 independent]

The poster won the Institute of Physics (IoP) Student Poster Prize in the mangetic confinement section.

P6. E. Belonohy, M. Hirsch, K. McCormick, G. Papp, G. Pokol, H. Thomsen, A. Werner, S. Zoletnik and the W7-AS Team
„Edge Instabilites in the High Density H-mode operation of W7-AS"
35th EPS Conference on Plasma Physics, Hersonissos, Crete, Greece
Europhysics Conference Abstracts 23D (2008), P2.034
[conference proceedings]

P7. E. Belonohy, K. Gál, O. Kardaun, P.T. Lang, B. Lovász and the ASDEX Upgrade Team
"Magnetic field dependence of pellet penetration"
37th EPS Conference on Plasma Physics, Dublin, Ireland
Europhysics Conference Abstracts 34A (2010) P5-143
[conference proceedings]

Further publication in refereed journals in the topic of the dissertation:

1. P.T. Lang, K. Lackner, M. Maraschek, B. Alper, E. Belonohy, K. Gál, J. Hobirk, A.Kallenbach, S. Kálvin, G. Kocsis,C.P. Perez van Thun, W. Suttrop, T. Szepesi, R. Wenninger, H. Zohm, the ASDEX Upgrade Team and JET-EFDA contributors
„Investigation of pellet-triggered MHD events in ASDEX Upgrade and JET"
Nuclear Fusion, 48 (2008) 095007
[refereed journal, impact factor: 3.303, citations: 9 out of 11 independent]

2. P.T. Lang, K. Lackner, M. Maraschek, B. Alper, E. Belonohy, K. Gál, J. Hobirk, A.Kallenbach, S. Kálvin, G. Kocsis,C.P. Perez van Thun, W. Suttrop, T. Szepesi, R. Wenninger, H. Zohm, the ASDEX Upgrade Team and JET-EFDA contributors
„ELM pacing investigations at JET with the new pellet launcher"
Nuclear Fusion, 51 (2011) 033010
[refereed journal, impact factor: 3.303, citations: 4 independent]

International presentations in the topic of the dissertation:

Conference:

1. „A Systematic Study of the Quasi-Coherent Mode in the High Density H-mode Regime of Wendelstein 7-AS"
PLASMA2007 – International Conference on Research and Applications of Plasmas
October 2007, Greifswald, Germany

Workshops, Meeting:

2. „Anomalous transport events on the W7-AS stellarator"
10th Workshopon Electric Fields, Structures and Relaxation in Plasmas
June 2007, Warsaw, Poland

3. „Quasi-Coherent Modes in the High Density H-mode of the W7-AS Stellarator”
EFTSOMP2008 – Workshop on Electric Fields, Turbulence and Self-Organisation in Magnetized Plasmas, Satellite Meeting of the 35th EPS Conference on Plasma Physics
June 2008, Hersonissos, Crete, Greece

4. „High Field Side Pellet Database and Penetration Depth Scaling – A Statistical Approach”
Fuelling of Magnetic Confinement Machines Workshop, Satellite Meeting of the 35th EPS Conference on Plasma Physics
June 2008, Hersonissos, Crete, Greece

5. “Pellet Penetration Depth Scaling Studies”
EFDA Meeting on Fuelling and Particle Control
March 2009, IPP Garching, Germany

6. “Quasi-Coherent Activity in ELM-free H-modes”
EFTSOMP2009 – Workshop on Electric Fields, Turbulence and Self-Organisation in Magnetized Plasmas, Satellite Meeting og the 36th EPS Conference on Plasma Physics
July 2009, Sofia, Bulgaria

International seminar:

7. „High Field Side Pellet Database and Scaling Studies – An Application of Statistical Methods in Plasma Physics”
ASDEX Upgrade Seminar
July 2006, Max-Planck-Institut für Plasmaphysik. Garching, Germany